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13. ABSTRACT (Maximum 200 Words) We obtained the following results, according to research areas. Performance Bounds: General bounds on the mean-square errors for discrete-time nonlinear filtering and for estimating general vector systems. EM arrays: Methods for target tracking, direction estimation, and interference cancellation, with passive EM vector sensors; detecting the wake of a ship using an airborne SQUID magnetic transducer; estimating range, velocity, and direction with active radar array; equalizing and estimating channels with communication antenna arrays in spatially correlated noise. Acoustic arrays: Beamforming using acoustic vector sensors (AVS's); fast wideband algorithms for locating airborne targets using a passive distributed array of AVS's; direction finding with an AVS array near a reflecting boundary; analysis of cross-correlations between wide-band noise components of an AVS. Chemical arrays: Methods for automatic environmental monitoring and land-mine detection and localization using chemical sensor arrays. Biomedicine: Estimating evoked dipole responses, and tracking a dynamic source with EEG/MEG sensor arrays; estimating mechanical properties of the heart using tagged-MRI; adaptive hearing aids.				
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Advanced-Sensor Signal Processing:

Over the last several years, we have introduced the use of several advanced sensors to signal processing. By incorporating novel sensor technologies and measurement models that make full use of the physical information available, we have added a new dimension to signal processing and considerably enhanced its practical utility. In recognition to our leadership and contribution in this area, we have invited to present a summary of this work in [1].

General Performance Bounds:

In [2] we derived a mean-square error lower bound for the discrete-time nonlinear filtering problem, based on the Van Trees' (posterior) version of the Cramér-Rao inequality. This lower bound is applicable to multidimensional nonlinear, possibly non-Gaussian, dynamical systems and is more general than the previous bounds in the literature. The case of a singular conditional distribution for the one step ahead state vector given the present state was considered. The bound was evaluated for three important examples: recursive estimation of slowly varying parameters of an autoregressive process, tracking a slowly varying frequency of a single cisoid in noise, and tracking the parameters of a sinusoidal frequency with sinusoidal phase modulation.

In [3], [4] we proposed a unified framework for the analysis of estimators of geometrical vector quantities and vector systems, through a collection of performance measures. Unlike standard performance indicators, these measures have intuitive geometrical and physical interpretations, are independent of the coordinate reference frame, and are applicable to arbitrary parameterizations of the unknown vector or system of vectors. For each measure we derived both finite-sample and asymptotic lower bounds that hold for large classes of estimators and serve as benchmarks for the assessment of estimation algorithms. Like the performance measures themselves, these bounds are independent of the reference coordinate frame and we discussed their use as system design criteria.

Electromagnetic Array Processing for Radar and Communications:

Our main original results on electromagnetic vector-sensor processing have appeared in a book chapter [5]. We introduced the concept of EM *vector sensors*, which measure the complete EM field at a single point, to the signal processing community. Such sensors are now commercially available. Using these sensors, we created methods for estimating the directions of arrival and polarization states of electromagnetic waves. To analyze their performance, we defined quality measures for estimating direction and orientation in 3D space, including mean-square angular error and covariance of vector-angular error, and derived lower bounds on them. These quality measures and bounds are not limited to EM waves and are already used by researchers in various fields. We conducted identifiability analyses that showed that with one vector sensor it is possible to find the directions and polarization ellipses of up to 3 sources. Thus, we determined that with one vector sensor it is possible to do what historically was done by an array of distributed scalar sensors. Furthermore, we showed that a vector sensor can resolve co-incident and very closely spaced sources based on polarization differences. This can be of considerable benefit. For example, in cellular communications it provides a new multiple access diversity mechanism for increasing base station capacity. We also proposed a very fast algorithm for finding the source direction and analyzed its asymptotic statistical performance. A patent has been awarded for this algorithm.

In [6] we developed two high-resolution methods for direction-of-arrival estimation with electromagnetic vector sensors. Both methods, of which the first is ESPRIT-based and the second MUSIC-based, are applicable to scenarios where completely polarized and incompletely polarized signals co-exist. The ESPRIT-based method is computationally efficient, but there must be three vector sensors with a specific sensor arrangement in order to apply the method. On the other hand, the MUSIC-based method, although involving more computations, can work without the constraint that the ESPRIT-based method faces. In addition, neither method requires *a priori* information regarding the numbers of completely polarized and incompletely polarized signals impinging on the array, and will inherently provide such information.

We developed in [7]-[9] a beamformer employing a single electromagnetic vector sensor. This beamformer is of minimum-noise-variance type, and is used for interference rejection. It creates a beam focused in both direction and polarization that minimizes interference from undesired sources (e.g. jammers). In this way it can do the work of multiple scalar polarization-selective sensors.

We considered two types of signals: one carries a single message, and the other carries two independent messages simultaneously. The state of polarization of the interferences under consideration ranged from completely polarized to unpolarized. To analyze the performance, we first obtained explicit expressions for the signal to interference-plus-noise ratio (SINR) in terms of the parameters of the desired signal, interference, and noise. Then we discussed some physical implications associated with the SINR expressions. Our SINR results provide a basis for effective interference suppression, as well as generation of dual-message signals in which there is minimum crosstalk.

The key advantages of our beamformer over current systems are that it:

- Works in three dimensions using only a single vector sensor, significantly simplifying receiver design and occupying very little space. Most current methods require a two-dimensional array to implement three-dimensional focusing.
- Exploits any polarization properties that the incoming signal may have. This provides a crucial criterion for distinguishing and isolating signals that may otherwise overlap too much for conventional systems.
- Extends easily to multiple sources with diverse carrier frequencies and polarizations, using multiple vector sensors as receivers.
- Distinguishes between sources without ambiguities, since it searches in both the polarization and direction domains. Existing methods suffer from frequency/localization ambiguities as they use only time delay information.

Numerical examples confirmed our analytical results.

In [10] we extended previous work to the space-time-polarization domain and applied vector sensor array processing to estimate the angles-of-arrival(AOAs) and delays of multipath channels. A MUSIC like algorithm for joint angle and delay estimation with a vector sensor array was derived. Simulation results showed that the space-time-polarization parameterization of the multipath channels can result in better accuracy and resolution performance.

In [11], [12] we presented two adaptive cross-product algorithms for tracking the direction to a moving source using an electromagnetic vector sensor. The first was a cross-product algorithm with a forgetting factor, for which we analyzed the performance and derived an asymptotic expression of the variance of angular estimation error. We found the optimal forgetting factor that minimizes this variance. The second was a Kalman filter combined with the cross-product algorithm, which is applicable when the angular acceleration of the source is approximately constant.

In [13], [14] we proposed an approach to localize multiple sources based on spatially distributed electric and magnetic component sensors. By jointly exploiting all available electromagnetic information as well as spatial diversity (time delays), this approach should outperform both a single vector-sensor and scalar-sensor arrays in accuracy of direction of arrival estimation.

In [15], [16], we derived Cramér-Rao bound (CRB) expressions for the range (time delay), velocity (Doppler shift), and direction of a point target using an active radar or sonar array. First, general CRB expressions were derived for an arbitrary signal waveform and a noise model that allows both spatial and temporal correlation. We discussed the relationship between the CRB and ambiguity function for this model. Then we specialized our CRB results to temporally uncorrelated noise and the practically important signal shape of a linear frequency modulated (chirp) pulse sequence. We computed the CRB for a 3-dimensional array with isotropic sensors in spatially uncorrelated noise and showed that it is a function

of the array geometry only through the “moments of inertia” of the array. The volume of the confidence region for the target’s location was proposed as a measure of accuracy. For this measure, we showed that the highest (and lowest) target location accuracy is achieved if the target lies along one of the principal axes of inertia of the array. Finally, we compared the location accuracies of several array geometries. For temporally uncorrelated noise and unknown spatially correlated noise, we presented in [17] maximum likelihood (ML) methods for active estimation of the time delay, Doppler shift, and direction.

In [18], [19] we addressed the problem of identifying and equalizing communication channels in the presence of strong co-channel interference (CCI). We considered the interference and noise as colored noise of unknown covariance and exploited the underlying structure and constraints of the transmitted data and channel outputs. The proposed algorithm optimizes a weighted least-squares cost function using an iterative reweighting alternating minimization procedure. Numerical examples were presented and showed that the proposed algorithm is capable of achieving reliable channel identification and equalization in the presence of strong CCI at moderate SNR.

In [20] we proposed a new approach to joint estimation of directions and arrival times of for multipath channels parameterized by a finite number of path gains, direction and time of arrivals. The proposed approach exploits *a priori* knowledge of the pulse shaping filters and array manifold. The significance of this approach is that the directions of arrival (DOA) and times of arrival (TOA) of the multipath signals can be estimated directly from the oversampled channel outputs without assuming channel stationarity over the time-slot, nor requiring a start-up sequence in each time-slot to obtain estimates of the channel.

We presented in [21], [22] ML methods for space-time fading channel estimation with an antenna array in spatially correlated noise having unknown covariance. The received signal was modeled as a linear combination of multipath-delayed and Doppler-shifted copies of the transmitted waveform. We considered structured and unstructured array response models, and derived the CRB for the unknown directions of arrival, time delays and Doppler

shifts. We also proposed coherent matched-filter and concentrated-likelihood receivers which account for the spatial noise covariance.

In [23], [24] we introduced methods for detecting the wake of a ship using an airborne SQUID magnetic transducer. Wake induced by motion of vessels may extend for tens of kilometers and exist for hours under certain conditions in open sea. This forms a useful feature for long-range ship detection. Our methods are applicable for passively detecting a ship wake using measurements obtained by an airborne SQUID magnetic transducer that measures the first-order gradients of the magnetic signature induced by the wake. Analytical formulas of wake magnetic gradients were derived to provide guidelines for the airborne detectors. We also derived probability bounds of wake detection for cross-correlation and square-law detectors, which are useful to predict the expected performance.

Acoustic Array Processing:

In [25] we considered the use of arrays of acoustic vector sensors for underwater direction-of-arrival estimation. Acoustic vector sensors measure the acoustic pressure and all three components of acoustic particle velocity at a single point. They provide enhanced performance over traditional pressure-sensor arrays, allowing the use of smaller apertures, and full bearing resolution with simple linear geometries. We conducted a detailed analysis of their optimum performance, in terms of the Cramer-Rao bound, for a single source. As a result we identified two distinct phenomena that account for their improved performance over standard systems: (i) an effective increase in signal-to-noise ratio (SNR) due to extra measurements of the inter-sensor phase shifts and (ii) extra independent bearing information arising from direct measurement of the velocity field's structure. By examining these phenomena separately, we determined conditions on the array's size, shape, and SNR, under which the use of vector sensors is most advantageous, and quantified that advantage.

We also extended beamforming and Capon direction estimation procedures for use with vector-sensor arrays. We showed that the extra velocity-field information removes all ambi-

guities such as grating lobes. This allows the use of simple structures for which fast direction estimation algorithms exist, e.g. a uniform linear array (ULA), to determine both the azimuth and elevation of a source (a conventional ULA can only determine conic angle). It also means that spatially undersampled arrays of vector sensors can be used to increase aperture and hence performance. Finally we derived large-sample approximations for the mean-square errors of these two estimators.

In [26] we carefully considered the effect of sensor placement on the direction-of-arrival estimation performance of an array of acoustic vector sensors. We derived expressions for the Cramer-Rao bound on the azimuth and elevation of a single source, for an array of arbitrary shape. Using this result, we found necessary and sufficient conditions on the geometry to ensure that the ability to estimate one of the bearing parameters is independent of knowledge of the other. We argued that these conditions provide a compelling criterion for array-shape design. We then considered a bound on the mean-square angular error, which is a very useful single measure of performance in three-dimensional bearing problems. Using this bound, we extended our previous conditions to provide a sufficient set of conditions that ensure the array's optimal performance is isotropic. We also determined that knowledge of the signal and noise powers makes no difference to the optimal ability to estimate the bearing.

In [27] we considered the passive direction-of-arrival (DOA) estimation problem using arrays of acoustic vector sensors located in a fluid, at or near a reflecting boundary. We formulated a general measurement model applicable to any planar surface, derived an expression for the Cramér-Rao bound (CRB) on the azimuth and elevation of a single source, and obtained a bound on the mean-square angular error (MSAE). We then examined two applications of great practical interest: hull-mounted and seabed arrays. For the former, we used three models for the hull: an ideal rigid surface for high frequency, an ideal pressure-release surface for low frequency, and a more complex, realistic layered model. For the seabed scenario we modeled the ocean floor as an absorptive liquid layer. For each application we used the CRB, MSAE bound, and beampatterns to quantify the advantages of using velocity and/or vector sensors instead of pressure sensors. For the hull-mounted application, we showed

that normal component velocity sensors overcome the well-known, low-frequency problem of small pressure signals without the need for an undesirable “stand-off” distance. For the seabed scenario, we also derived a fast wideband estimator of the source location using a single vector sensor.

Most array processing methods require knowledge of the correlation structure of the noise. While such information may sometimes be obtained from measurements made when no sources are present, this may not always be possible. Furthermore, measurements made *in-situ* can hardly be used to analyze system performance before deployment. The development of models of the correlation structure under various environmental assumptions is therefore very important. In [28] we obtained integral and closed form expressions for the auto- and cross-correlations between the components of an acoustic vector sensor (AVS) for a wideband noise field, under the following assumptions concerning its spatial distribution: (i) azimuthal independence; (ii) azimuthal independence and elevational symmetry, and (iii) spherical isotropy. We also derived expressions for the cross-covariances between all components of two spatially displaced AVS's in a narrowband noise field under the same assumptions. These results can be used to determine the noise covariance matrix of an array of acoustic vector sensors in ambient noise. We applied them to a uniform linear AVS array to assess its beamforming capabilities and localization accuracy, via the Cramér-Rao bound, in isotropic and anisotropic noise.

In [29], [30], and [31], we derived fast wideband algorithms for determining the bearing and 3-D position of a target using a distributed array of acoustic vector sensors (AVS's) situated in freespace or on a reflecting boundary. Each AVS locally estimates the bearing from its location to the target using a rapid wideband estimator we developed based on the acoustic intensity vector; adaptations of beamforming-based bearing estimators were also discussed. The local bearing estimates are then transmitted to a central processor where they are combined to determine the 3-D position. Closed-form weighted least-squares (WLS) and reweighted least-squares algorithms were proposed to achieve this. A bound on the mean-square angular error of the local bearing estimates was obtained, and used

along with the data to adaptively determine the weights for the WLS routine. In addition a measure of potential 3-D location performance for the distributed system was developed based a two stage application of the Cramér-Rao bound. The results are relevant to the localization of underwater and airborne sources using freely-drifting, seabed, and ground sensors. Numerical simulations were used to illustrate the results.

We have graduated Malcolm Hawkes whose work on acoustic-vector sensor processing is summarized in his PhD thesis [32].

In [33] we propose an FFT based algorithm for implementing adaptive directionality of dual microphone application systems such as hearing aids, etc. We show theoretically and by simulation results that the proposed scheme can provide an adaptive and effective reduction of the noise that is in different direction from the one of the target signal. We also discuss in more details this proposed scheme from the practical application and hardware implementation points of view. In comparison with other available methods, the proposed scheme has the following advantages. It provides: 1. a simple and realizable implementation structure; 2. the elimination of an additional delay processing unit for endfire orientation microphones; 3. an effective solution of microphone mismatch problem and 4. the elimination of the assumption that the target signal must be exactly straight ahead. With these features, this proposed scheme could provide a new tool to implement adaptive directionality in related application fields.

Chemical Array Processing for Environmental Monitoring:

In [34], [35] we developed methods for automatic environmental monitoring of disposal sites on the deep ocean floor using chemical sensor arrays and statistical hypothesis testing. Such sites have been proposed for the relocation of waste materials dredged from harbors and shipping channels (for more details see the transitions section below). We modeled the transport of pollutants as a diffusion process and derived the associated concentration distribution. To derive the measurement and statistical models we exploited the spatial and temporal evolu-

tion of the concentration distribution. We proposed two detectors, the generalized likelihood ratio (GLR) test and the mean detector. The GLR detector gives a higher performance and is applicable when the physical model is reliable, while the mean detector is useful when a precise model is not available. To analyze the performance of both detectors we derived expressions for the probabilities of detection and false alarm. We then proposed several algorithms for the design of chemical sensor arrays satisfying criteria specified in terms of these probabilities, as well as optimal selection of number of sensors and time samples. To illustrate the applicability of our results we determined the optimal arrays for various set of model parameters and design criteria.

In [36], [37] we developed methods for automatic detection and localization of landmines using chemical sensor arrays and statistical signal processing techniques. The transport of explosive vapors emanating from buried landmines was modeled as a diffusion process in a two-layered system consisting of ground and air. The measurement and statistical models were then obtained from the associated concentration distribution. We derived two detectors, the generalized likelihood ratio (GLR) test and the mean detector, and determined their performance in terms of the probabilities of false alarm and detection. To determine the unknown location of a landmine we derived a maximum likelihood (ML) estimation algorithm and evaluate its performance by computing the Cramer-Rao bound. The results were applied to the design of chemical sensor arrays, satisfying criteria specified in terms of detection and estimation performance measures, and for optimally selecting the number and positions of sensors and the number of time samples. To illustrate the potential of the proposed techniques in a realistic demining scenario, we derived a moving-sensor algorithm, in which the stationary sensor array is replaced by a single moving sensor. Numerical examples were given to demonstrate the applicability of our results.

EEG/MEG Array Processing:

In [38]-[40] we developed maximum likelihood (ML) methods for estimating evoked dipole responses with electroencephalography (EEG) and magnetoencephalography (MEG) sensor

arrays, which allow for spatially correlated noise between sensors with unknown covariance. The electric source was modeled as a collection of current dipoles at fixed locations and the head as a spherical conductor. The dipoles' moments were permitted to vary with time as linear combinations of parametric or non-parametric basis functions. We estimated the dipoles' locations and moments, and derived the Cramér-Rao bound for the unknown parameters. We also proposed an ML-based method for scanning the brain response data, which can be used to initialize the multi-dimensional search required to obtain the true dipole location estimates. We showed that the derived ML estimates are asymptotically more efficient than the commonly used nonlinear least square estimates by showing that the difference in their asymptotic variances is negative semidefinite. We introduced a goodness-of-fit measure accounting for multiple time snapshots and correlated noise. Numerical examples with both simulated and experimental data were presented to demonstrate the performance of the proposed method.

In [41] we further discussed the case when the dipoles have fixed orientations in time. We estimated the dipoles' locations and moments, and derive the Fisher information matrix for the unknown parameters. We also proposed an array optimization criterion based on minimizing the volume of the linearized confidence region.

In [42] we derived a generalized least squares (GLS) method for estimating propagating dipole sources using EEG and MEG sensor arrays. The dipole locations varied in time according to a parametric model, whereas their moments varied arbitrarily from one time point to another. We also derived the Cramér-Rao bound for the trajectory parameters. We then extended the above method to account for unknown spatially correlated noise. This method has potential applicability for epilepsy patients.

In [43]-[45] we derived Cramér-Rao bounds on the errors of estimating a single dipole's location and moment using EEG, MEG and combined EEG/MEG modality. We used realistic head models based on knowledge of surfaces separating tissues of different conductivities, obtained from magnetic resonance (MR) or computer tomography (CT) imaging systems.

The electric potentials and magnetic field components at the respective sensors were obtained as functions of the source parameters through integral equations. These equations were formulated for solution by the boundary or the finite element method (BEM or FEM), with a weighted residuals technique. We presented a unified framework for the measurements computed by these methods that enables the derivation of the bounds. The resulting bounds may be used, for instance, to construct the confidence regions in dipole localization, and to choose the best configuration of sensors for a given patient and region of expected source location. Numerical results demonstrated an application for showing regions of good and poor expected accuracy in estimating the source parameters, based on a real EEG/MEG system.

In [46]–[47] we analyzed fundamental limitations in estimating the position, orientation and intensity of dynamic brain sources with data from (EEG/MEG). We derive the Cramer-Rao lower bound on the covariance of the estimated parameters of a dynamic dipole source. Our results extended previous work on parameter estimation of a fixed brain source through computing the CRB for nonlinear dynamical source models.

Estimating Mechanical Properties of the Heart Using MRI:

We presented in [48], [49] a new method for determining material properties of the myocardium. Changes in these properties can cause certain cardiac dysfunctions such as heart failure, ischemic heart disease, etc. Such changes can pre-date these dysfunctions and so serve as an early indicator of heart disease. We developed a model to relate the strain at various locations during the whole heart cycle to the material parameters, which are then estimated by minimizing a distance measure between the predicted strain and strain measurements obtained from tagged MRI images. Our approach combines a finite-element formulation and dynamic modeling, followed by a nonlinear least-squares optimization. We based our model on the material's stiffness tensor of anisotropic and non-homogeneous myocardium, so eliminating assumptions needed for the existence of a strain energy potential required in the standard approach. By exploiting the dynamics of heart-wall motion we achieved better

performance in terms of estimation error.

Transitions:

Our analytical results on performance for radar sensor arrays in [16], [17] are applied to the TechSat21 system. TechSat21, in general, is a radar system using an array of microsatellites. [See <http://www.vs.afrl.af.mil/VSD/TechSat21/>]. The purpose is to estimate direction, range, and velocity of a ground moving target. Our results are used to predict the performance of this system (e.g. accuracy of estimating the above target parameters in terms of Cramer-Rao bounds and ambiguity functions) and optimally design its configuration. We are also exploring the use of our ideas of vector sensors, which should give a great benefit of removing ambiguities (grating lobes) in direction finding. This work is done in collaboration with Dr. John Garnham [Phillips Laboratory, VTRA, telephone: (505) 846-7224], who provides us with the numerical data for this system.

Our idea of acoustic vector-sensor processing is being pursued by researchers at NUWC in Newport and by the NAVY ASTO (advanced systems and technology) office. Our results are applied to locate sources with high accuracy using a small-size acoustic sensor array. The researchers at NUWC are exploring the potential advantage of acoustic vector sensors for use in hull-mounted applications, in particular conformal submarine bow-dome arrays. They are conducting experiments to confirm our analytical results. We are collaborating with them on the analysis and simulation of specific scenarios, and provide them with coded algorithms for the processing of their raw measurements and integration into the experimental hardware and act as consultants. The first and second stages of this project were successfully concluded with demonstrations of our techniques in a water tank in December 1998 and July 2000. The researchers at NUWC are now moving to the third round of experiments that will take place in a lake, and in which we shall again be involved. The project will then move to final experimental stage involving sensors mounted on a sea going vessel. ASTO has recently transitioned the research from category 6.1 to categories 6.2, 6.3 and 6.4. It has also created a working group of people from academia and industry to further develop and investigate

the use of the new concept for hull-mounted velocity sensors. The NUWC project is headed by Dr. Ben Cray [NUWC, Newport, telephone 401-841-7505 ext. 38454]. The ASTO project is headed by Commander John Polcari and Mr. Mike Traweek [PEO(USW) ASTO G-4, Undersea Warfare, telephone: (703) 604-6013 ext. 527].

Our results on chemical sensor array processing have been pursued by DARPA and NRL's Stennis Space Center to design procedures for environmental monitoring of disposal sites. The annual buildup of sediment in U.S. ports and harbors must be removed in order to avoid detrimental effects to U.S. Naval operations and maritime trade. It has been proposed to relocate the dredged material in new disposal sites in the abyssal ocean. Since the dredged material may contain pollutants and toxins, environmental and political concerns dictate that monitoring of pollutants near the disposal sites be performed. DARPA and NRL has awarded us and a group of researchers 6.3 grants to develop techniques for automatic detection of pollutants at deep ocean relocation (DOR) sites on the abyssal sea floor, using a distributed co-operative chemical sensor array. These grants were a transition from our original research. The sponsors of this grant were Dr. Philip Valent [telephone 601-688-4650] and Dr. David Young [telephone 601-688-5507].

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